Reconciling cosmic dipolar tensions with a gigaparsec void

Qianhang Ding 丁乾航
The Hong Kong University of Science and Technology

Reference: 1912.12600, Qianhang Ding, Tomohiro Nakama, Yi Wang
2211.06857, Tingqi Cai, Qianhang Ding, Yi Wang

Cosmology from Home 2023

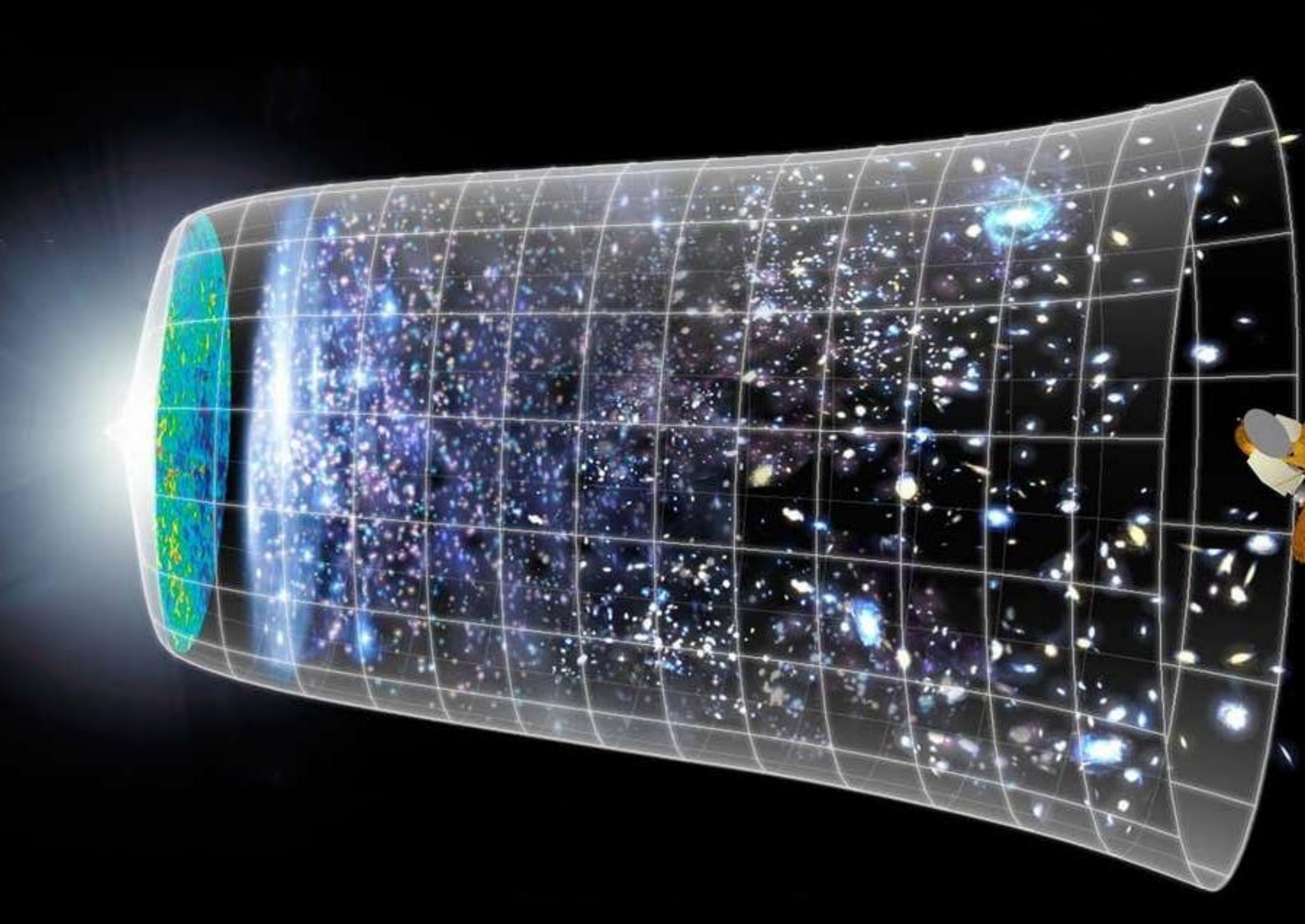


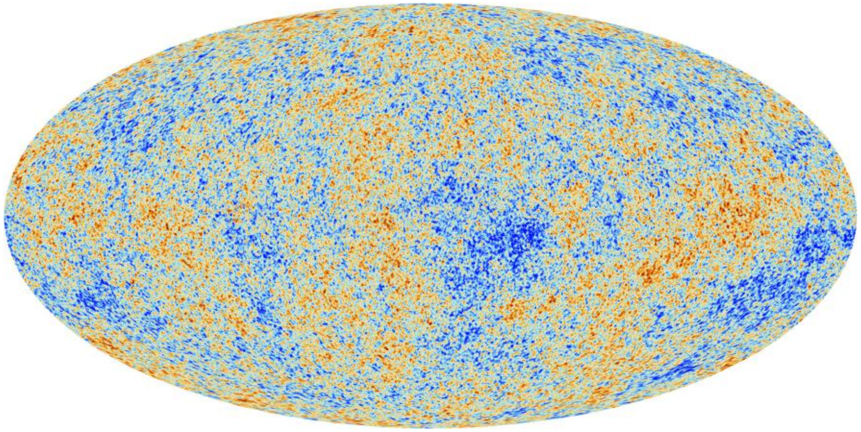
Image Credit: NASA

Cosmological Principle

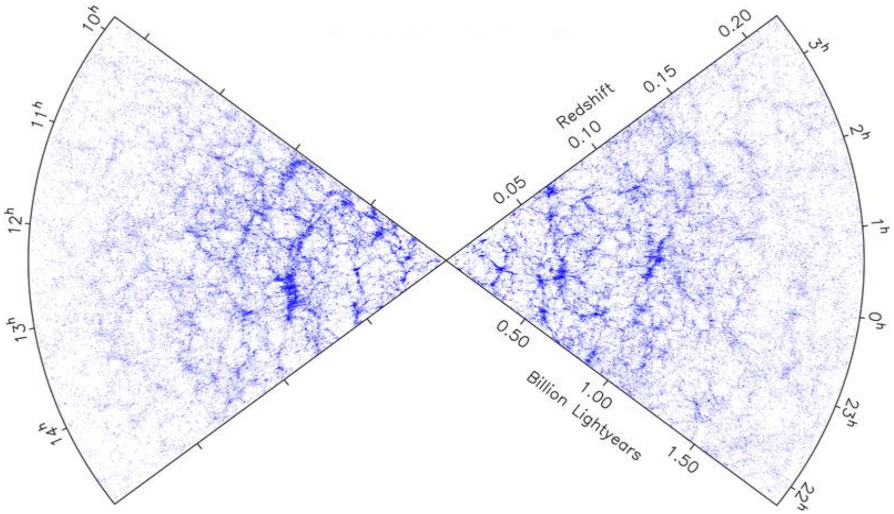
The Universe is *homogeneous* and *isotropic* on large scale, independent of location.

⇩

The law of physics should be the same at different positions of the Universe



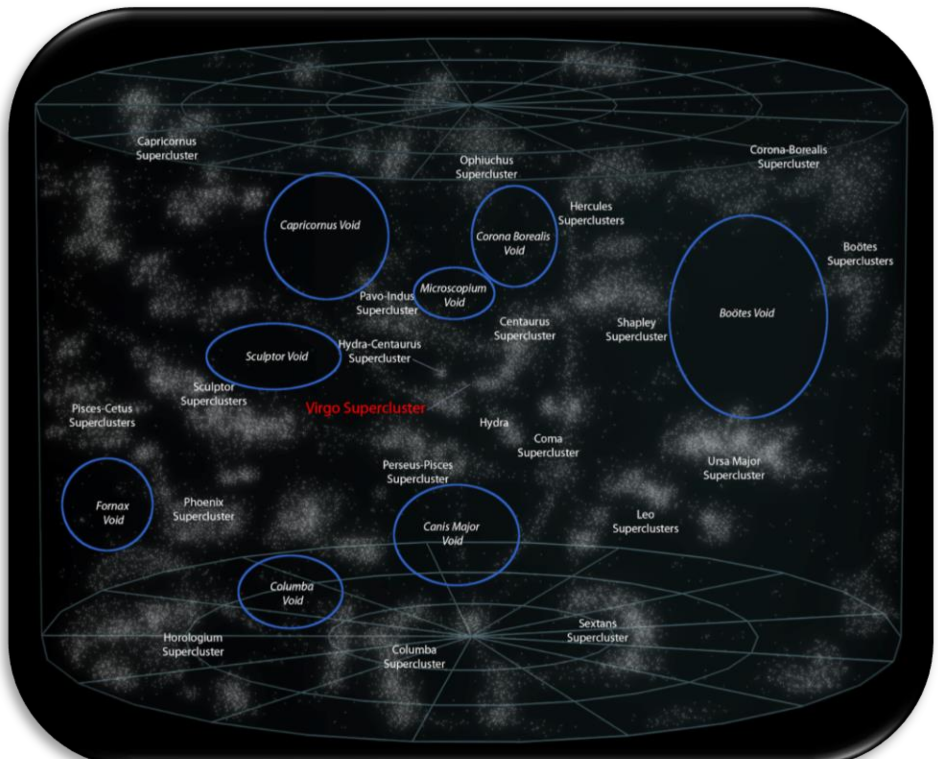
Cosmic microwave background



Large scale structure

Cosmic Inhomogeneity

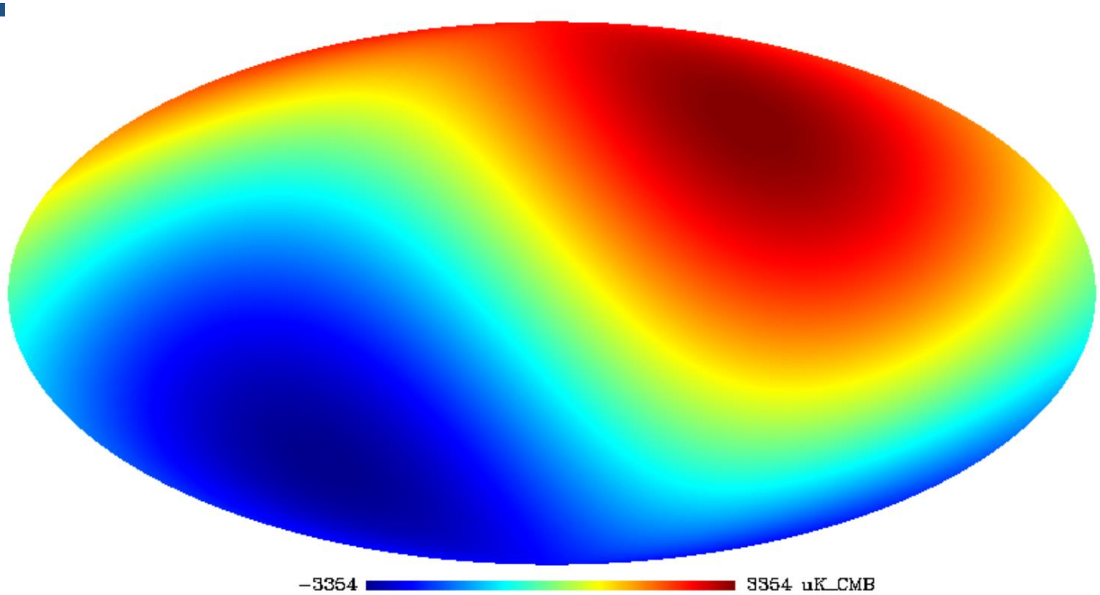
The List of Voids

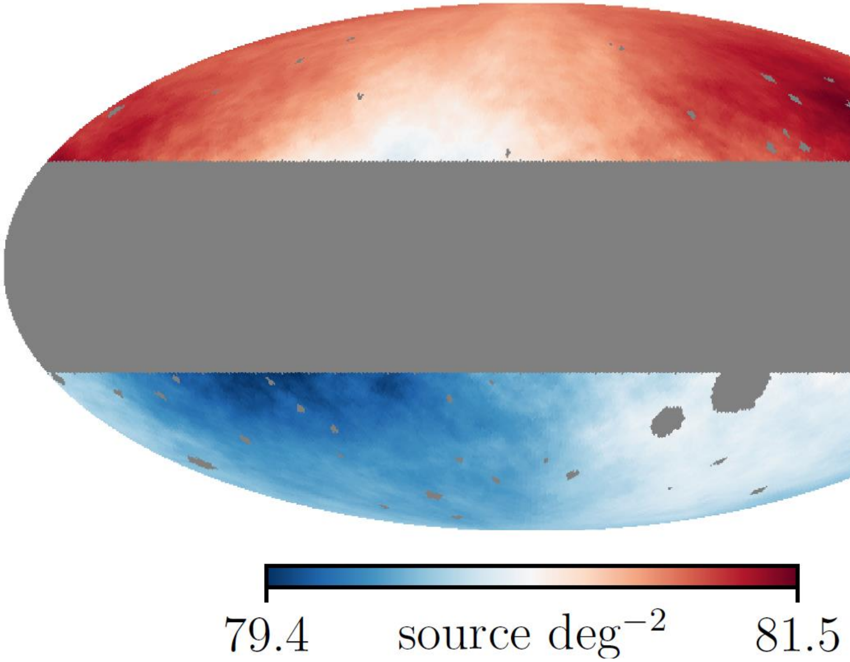


KBC Void
308 Mpc

Cosmic Anisotropy

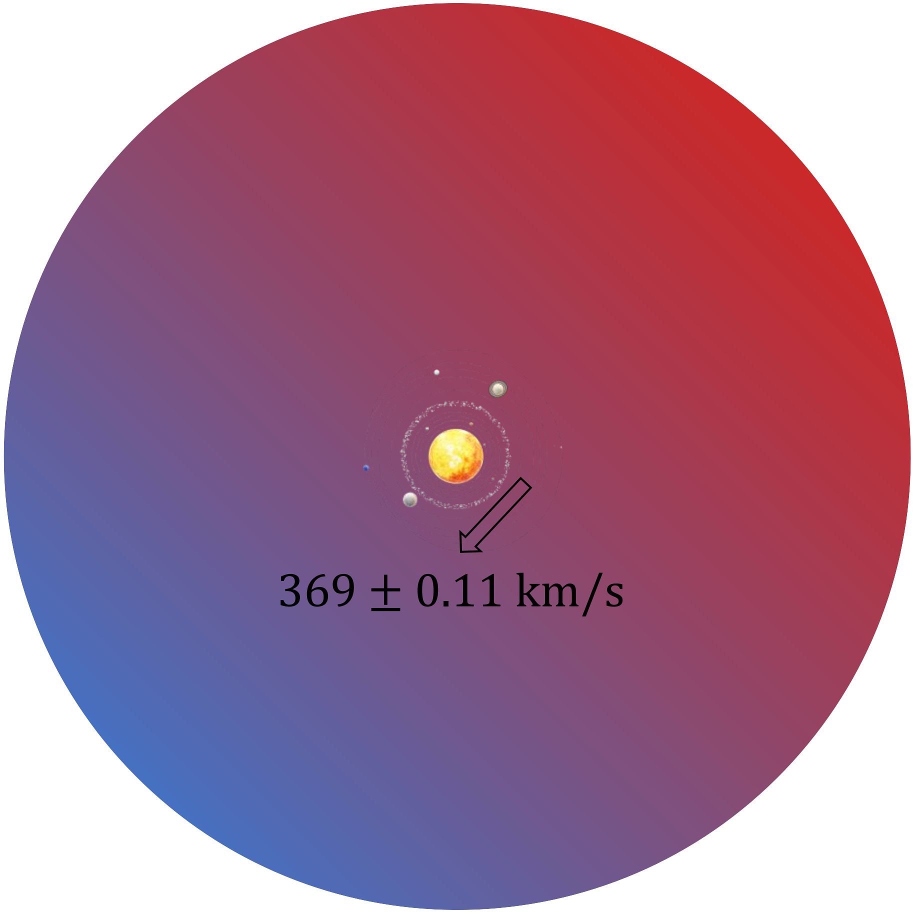
CMB Temperature Dipole
$\mathcal{D} \sim 10^{-3}$
$(264^{\circ}, 48^{\circ})$





Quasar Number Dipole
$\mathcal{D} \sim 10^{-2}$
$(233^{\circ}, 34^{\circ})$

Potential Explanation



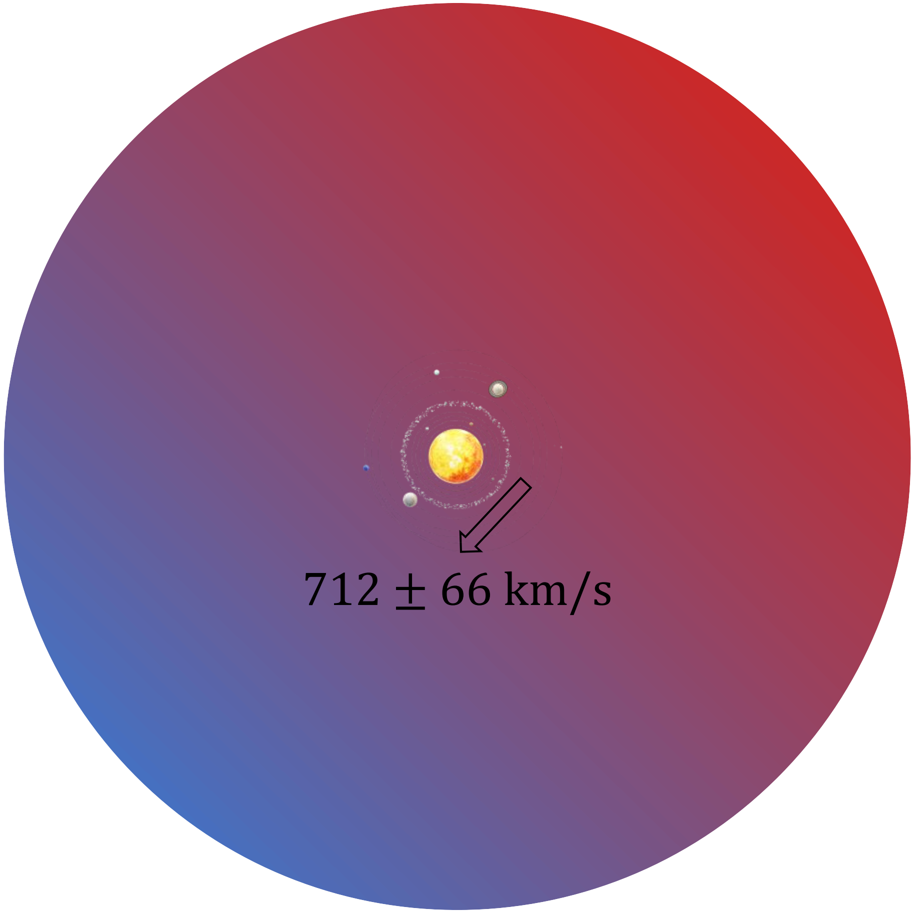
Doppler effect in CMB temperature

$$T' = \gamma(1 + \beta \cos\theta)\, T$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \quad \beta = \frac{v}{c}$$

$$\mathcal{D} \cong \frac{v}{c}$$

Potential Explanation



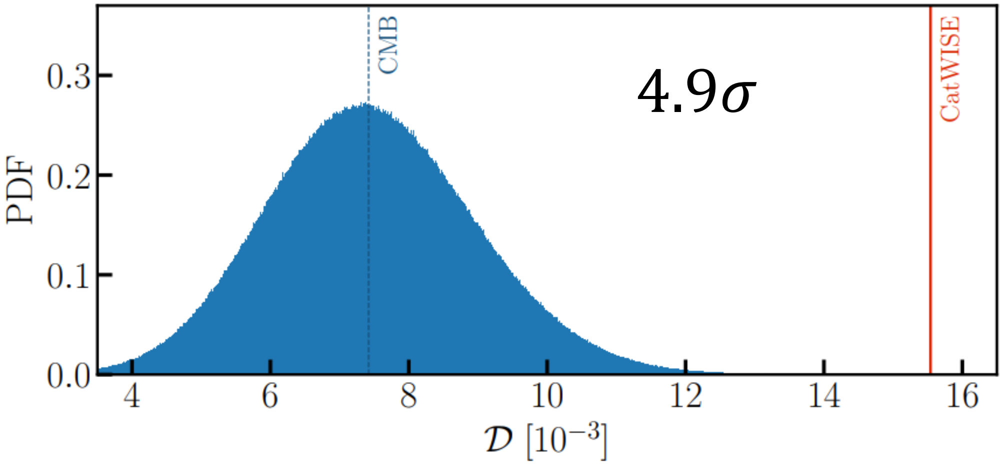
Doppler effect and aberration in quasar number counting

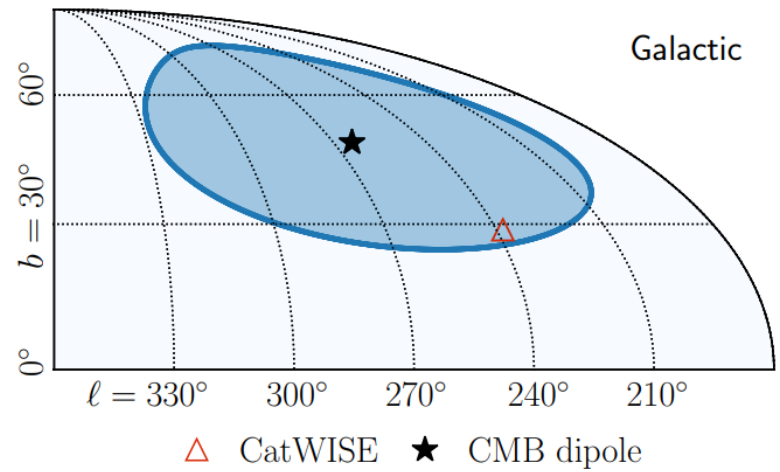
$$\nu_o = \nu_r \delta(v)$$

$$S \propto \nu^{-\alpha} \qquad \frac{dN}{d\Omega} \propto S^{-x}$$

$$\mathcal{D} \cong [2 + x(1+\alpha)]\frac{v}{c}$$

Dipolar Tension





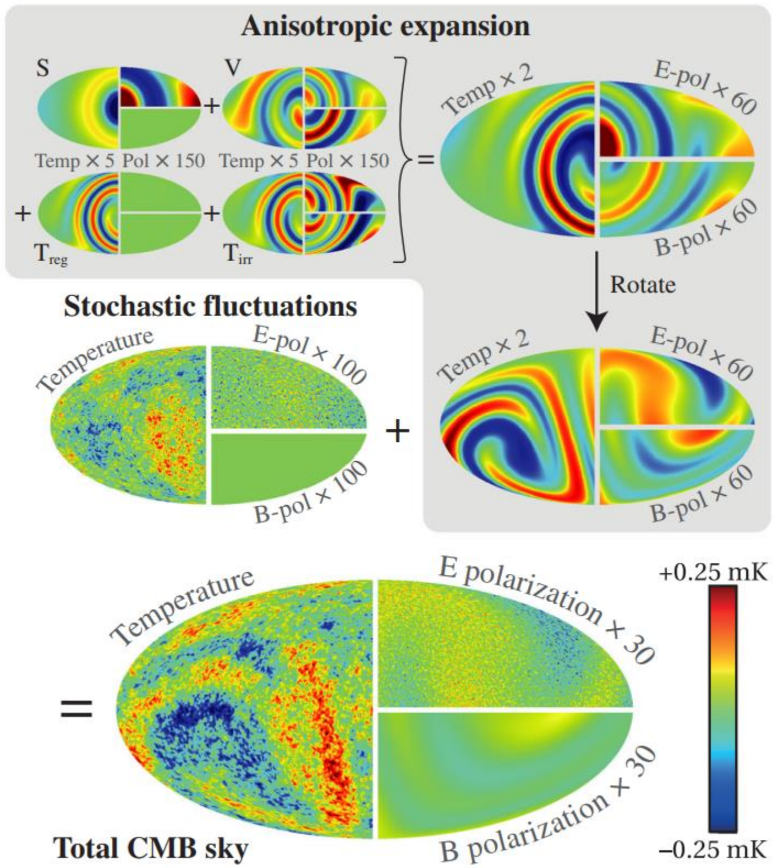
Secrest, Nathan J., et al. "A test of the cosmological principle with quasars." *The Astrophysical journal letters* 908.2 (2021): L51.

Global Anisotropy

Constraints on Bianchi cosmology

$$\frac{\sigma_V}{H} < 4.7 \times 10^{-11}$$

"How Isotropic is the Universe?", D. Saadeh, S. M. Feeney, A. Pontzen, H. V. Peiris, and J. D. McEwen, PRL



Rotating Universe

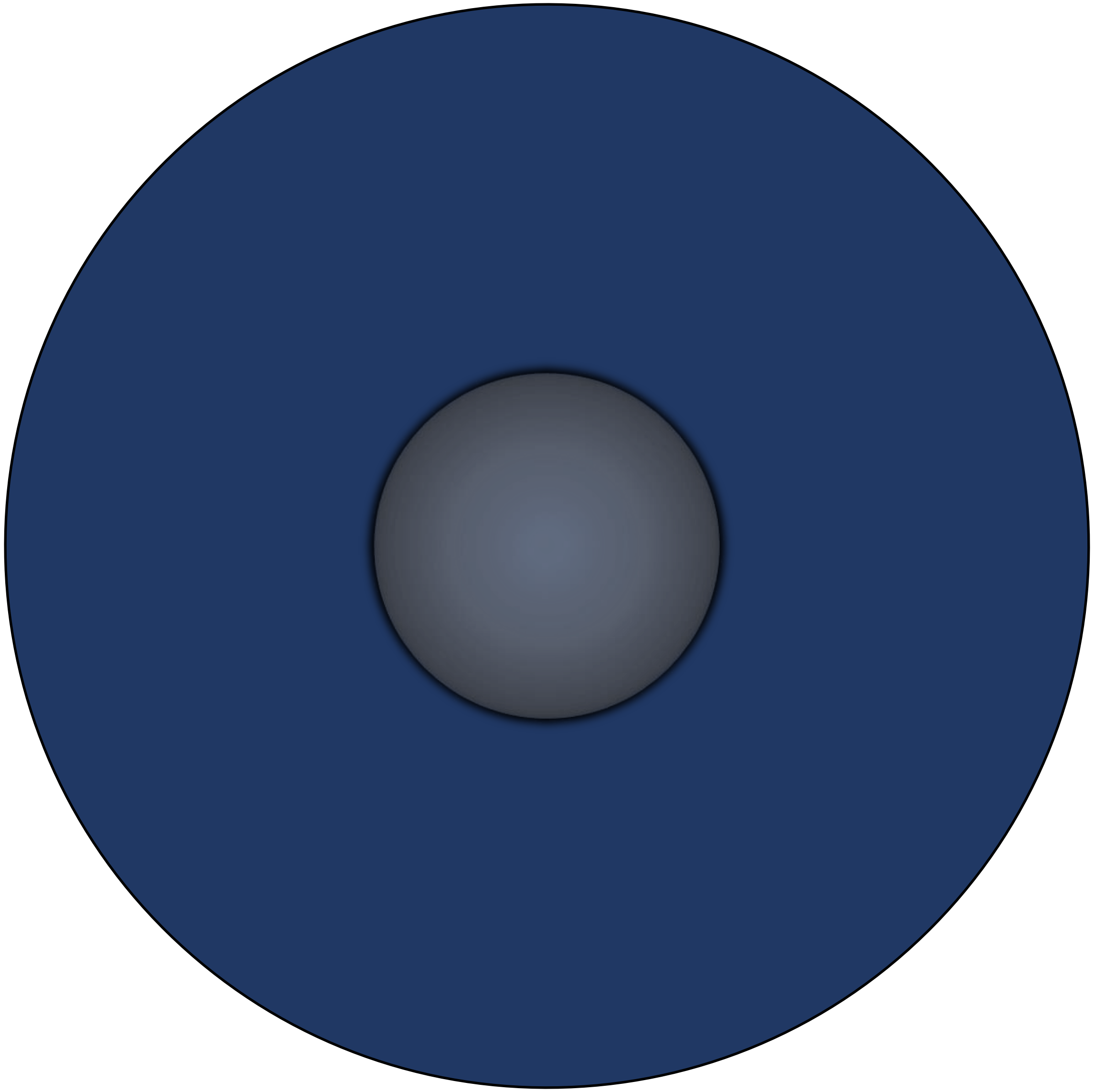
Angular velocity

$$\omega < 10^{-9} rad/yr$$

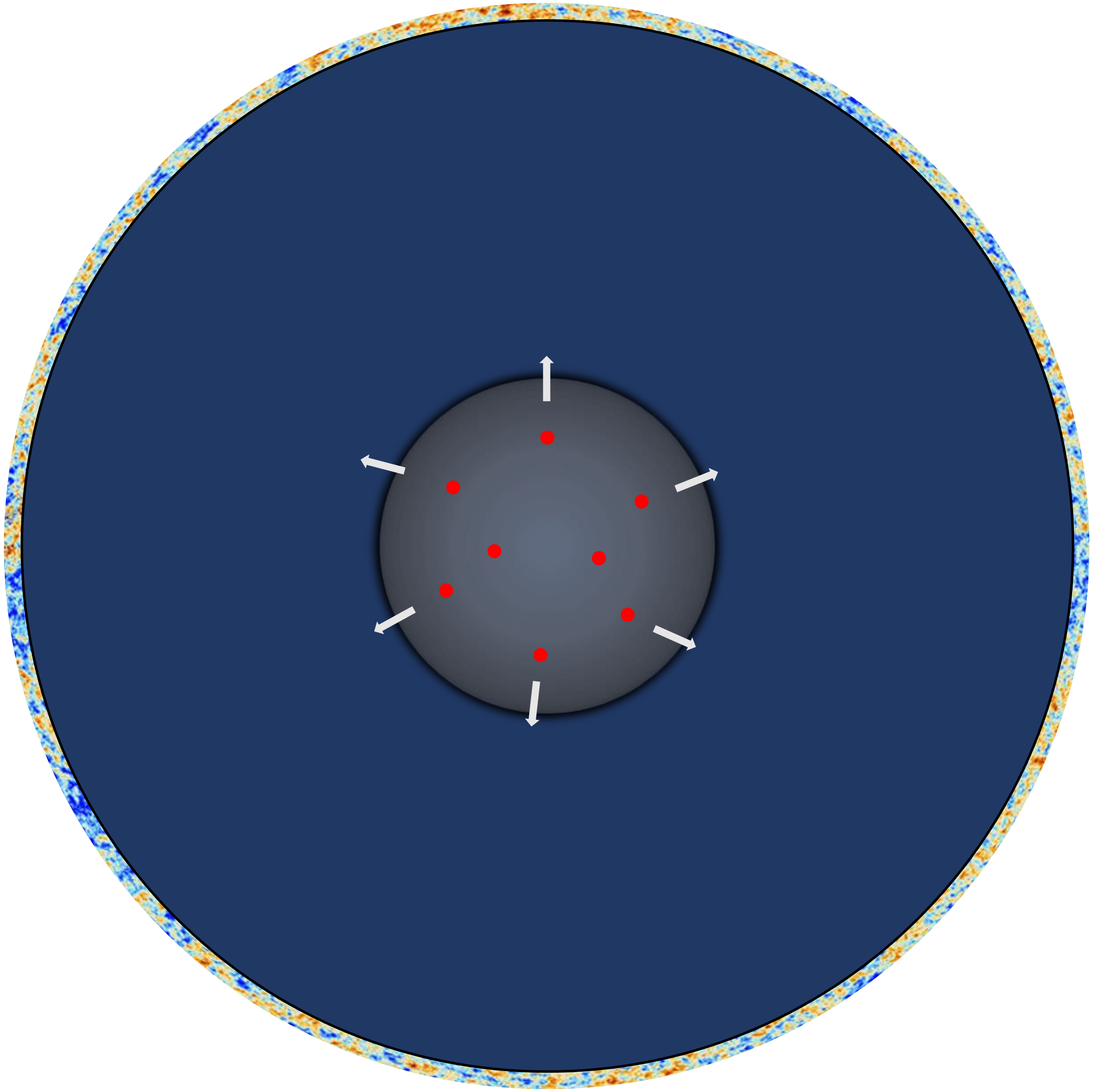
"Is the Universe rotating?", S.-C. Su and M.-C. Chu, APJ

A local structure may exist and influence the observations

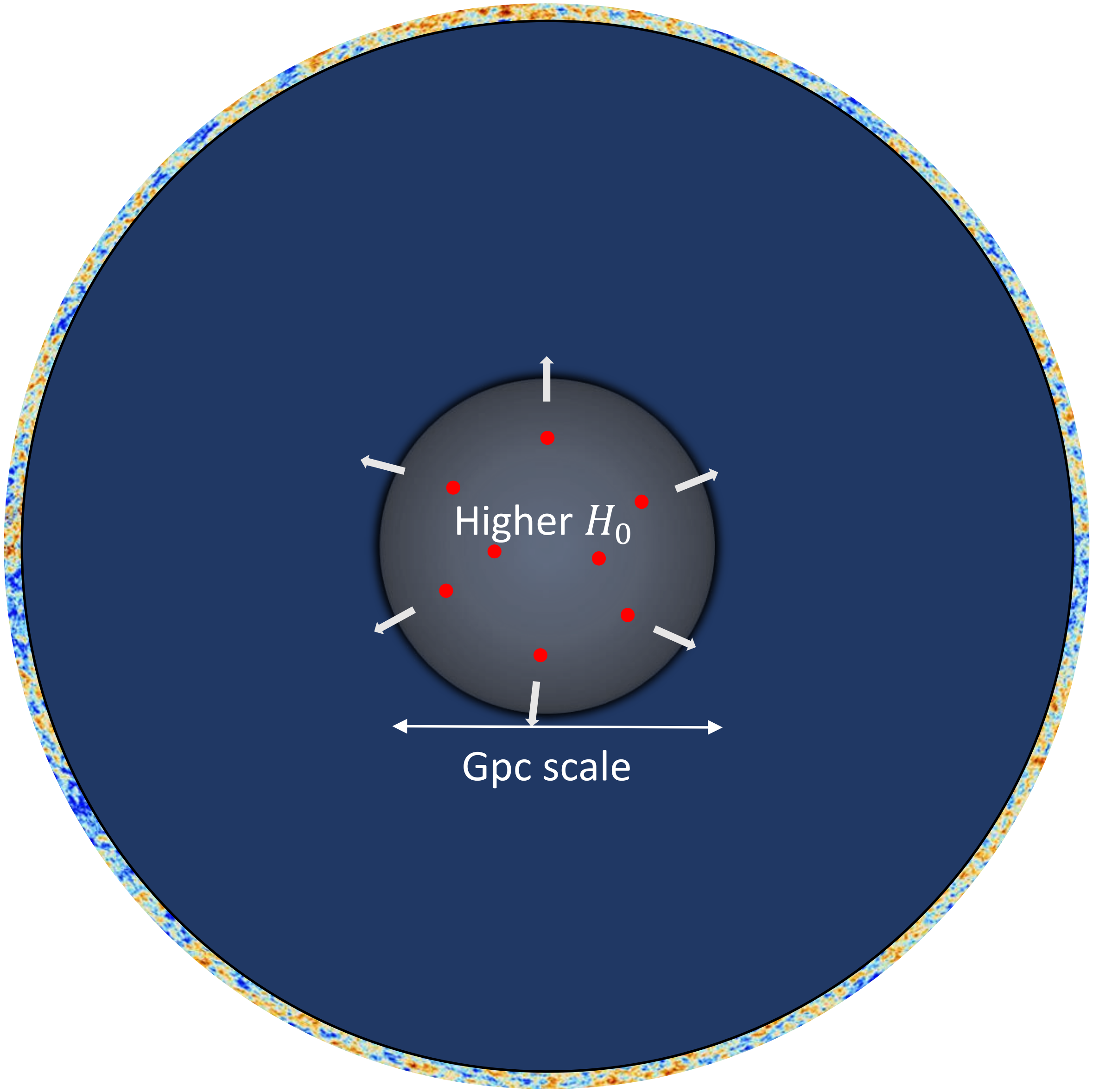
A Local Void



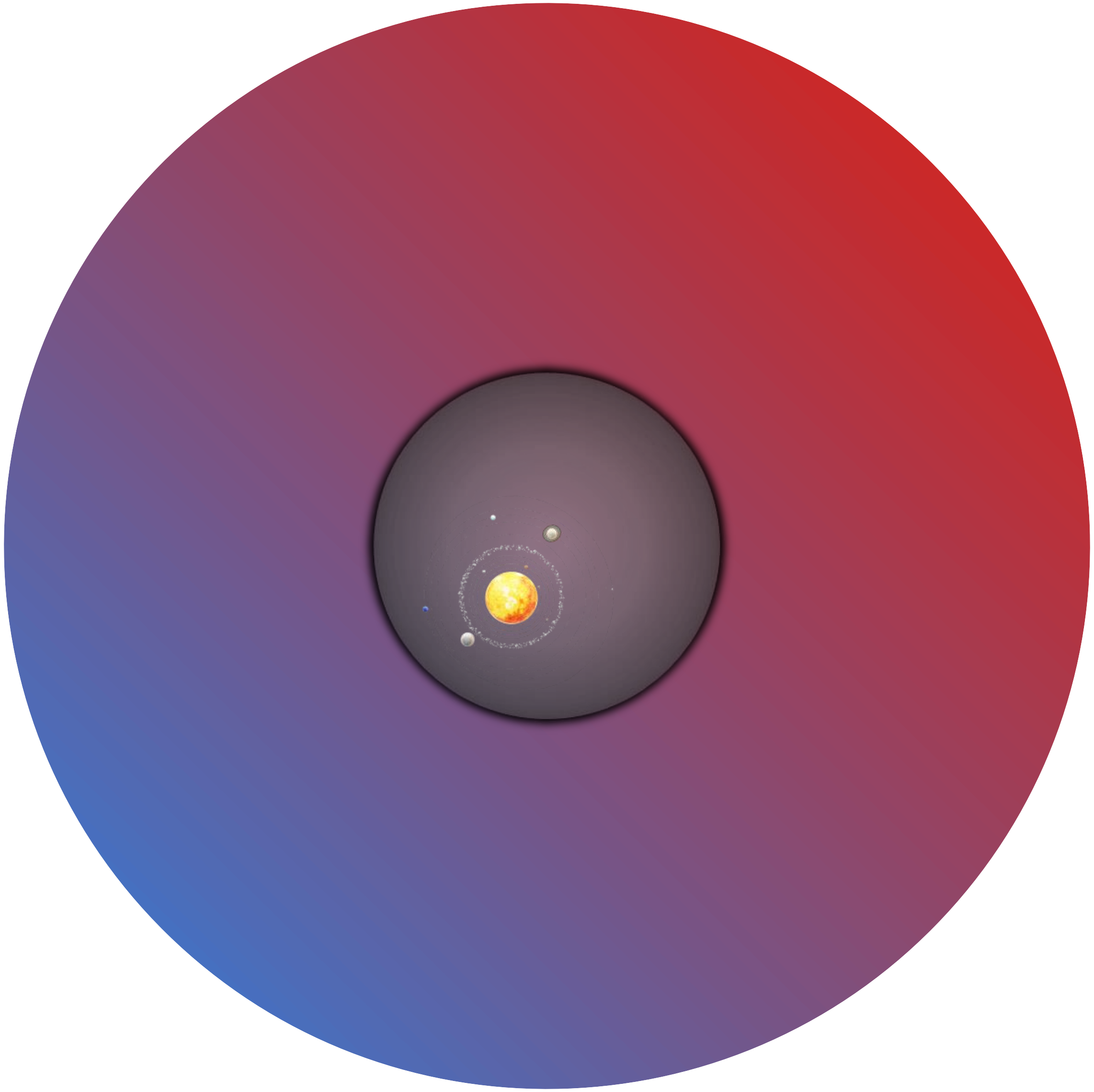
A Local Void & H_0



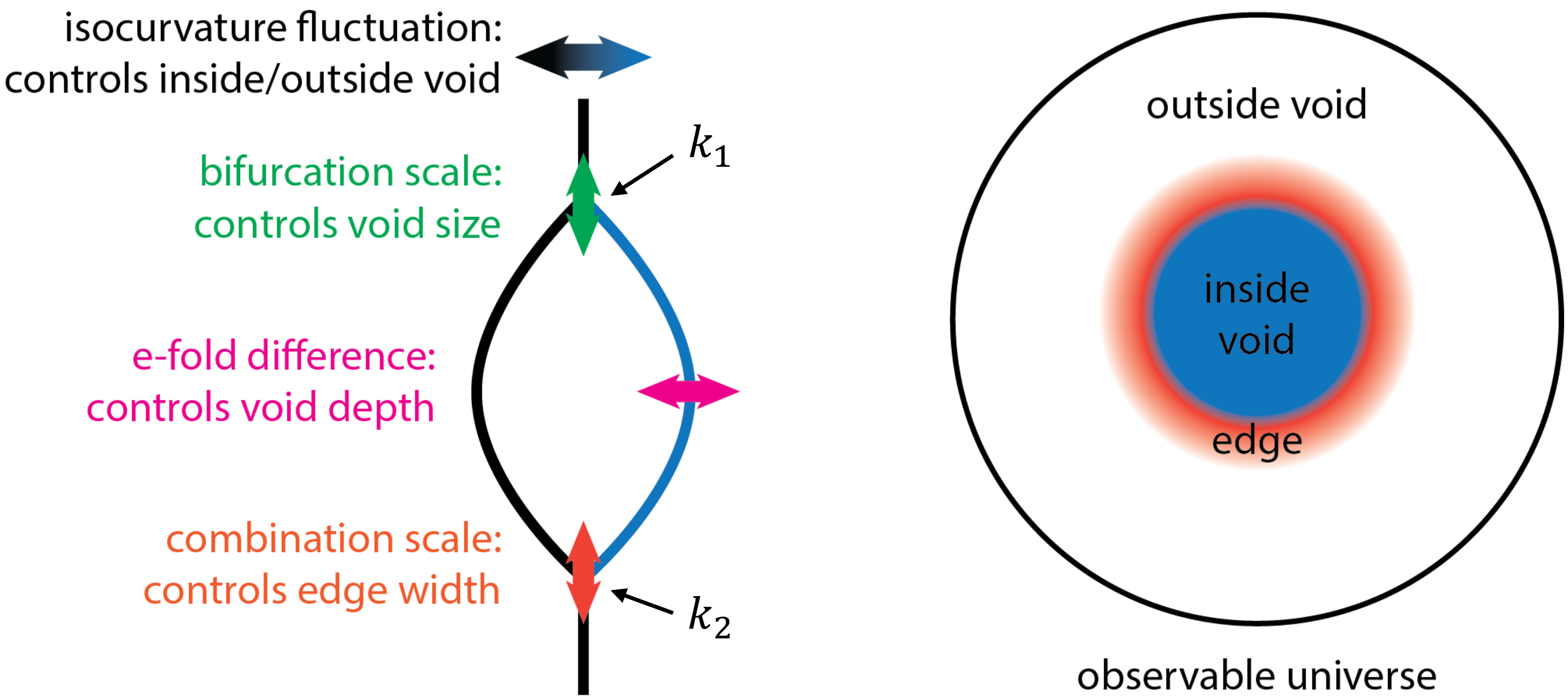
A Local Void & H_0



A Local Void & Dipole



Multi-Stream Inflation



We parameterize the void profile by introducing δ_V, r_V and Δ_r

$$\delta(r) = \delta_V \frac{1 - \tanh((r - r_V)/2\Delta_r)}{1 + \tanh(r_V/2\Delta_r)}$$

Here, the void shape is decided by the multi-stream inflation potential

$$\delta_V \sim \delta N, \quad r_V \sim \frac{1}{k_1}, \quad \Delta_r \sim \frac{1}{k_1} - \frac{1}{k_2}$$

Hubble tension in a Gpc-scale local void

Qianhang Ding, Tomohiro
Nakama, Yi Wang, 1912.12600

LTB Metric & H_0

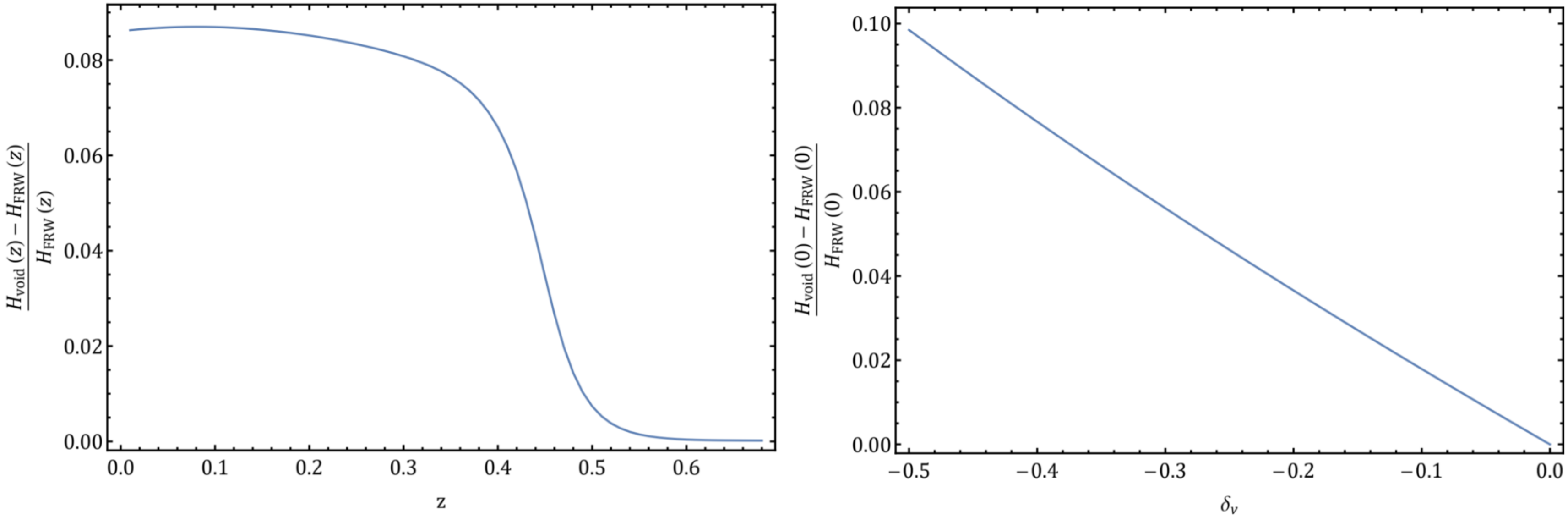
In order to describe spacetime in void model, we use the Lemaitre-Tolman-Bondi (LTB) metric:

$$ds^2 = c^2dt^2 - \frac{R'(r,t)^2}{1-k(r)}dr^2 - R^2(r,t)d\Omega^2$$

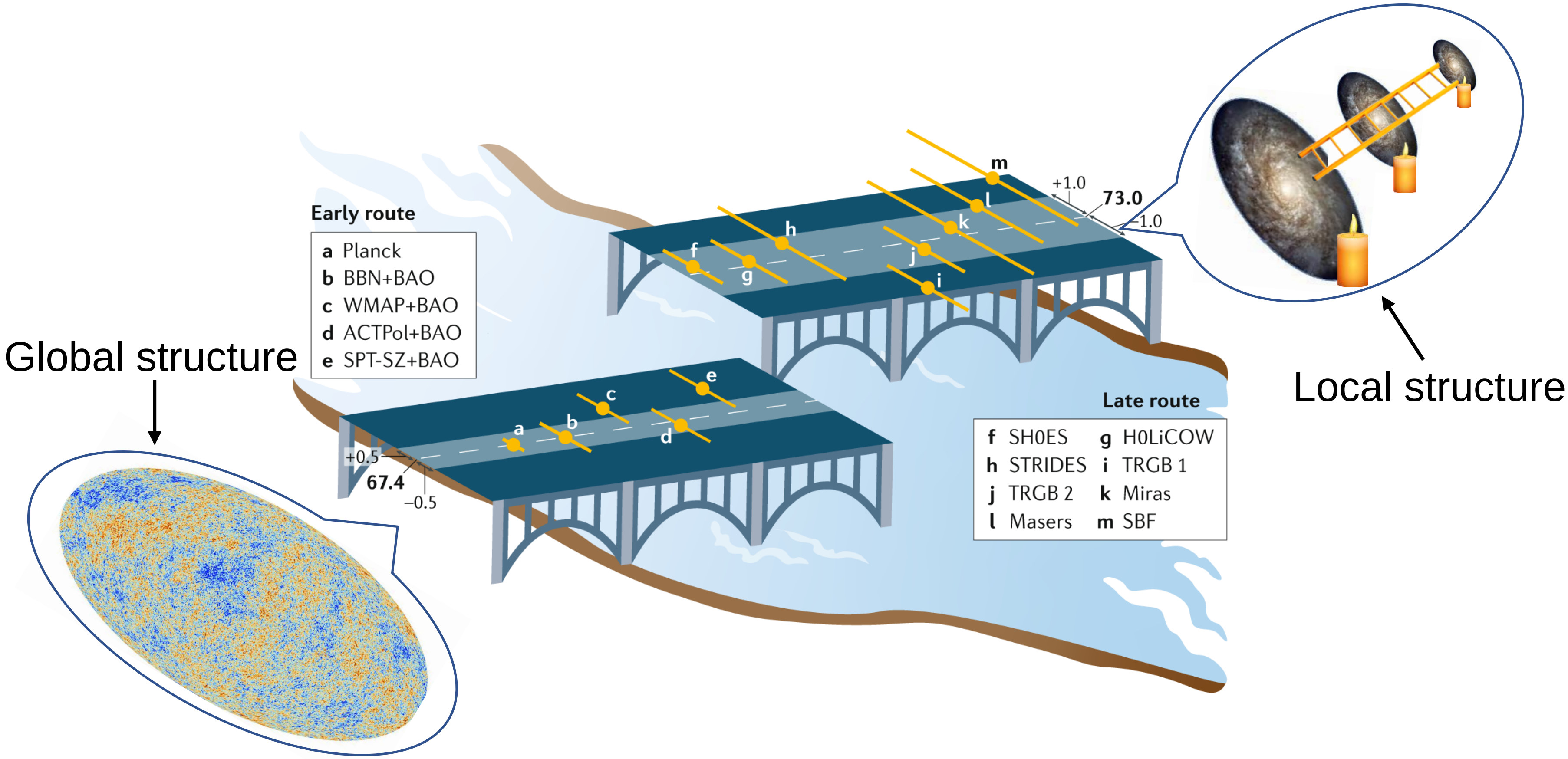
The Friedmann equation in LTB metric is

$$H(r,t)^2 = H_0(r)^2\left(\Omega_M(r)\frac{R_0(r)^3}{R(r,t)^3} + \Omega_k(r)\frac{R_0(r)^2}{R(r,t)^2} + \Omega_\Lambda(r)\right)$$

Which can introduce different Hubble parameters in a local void



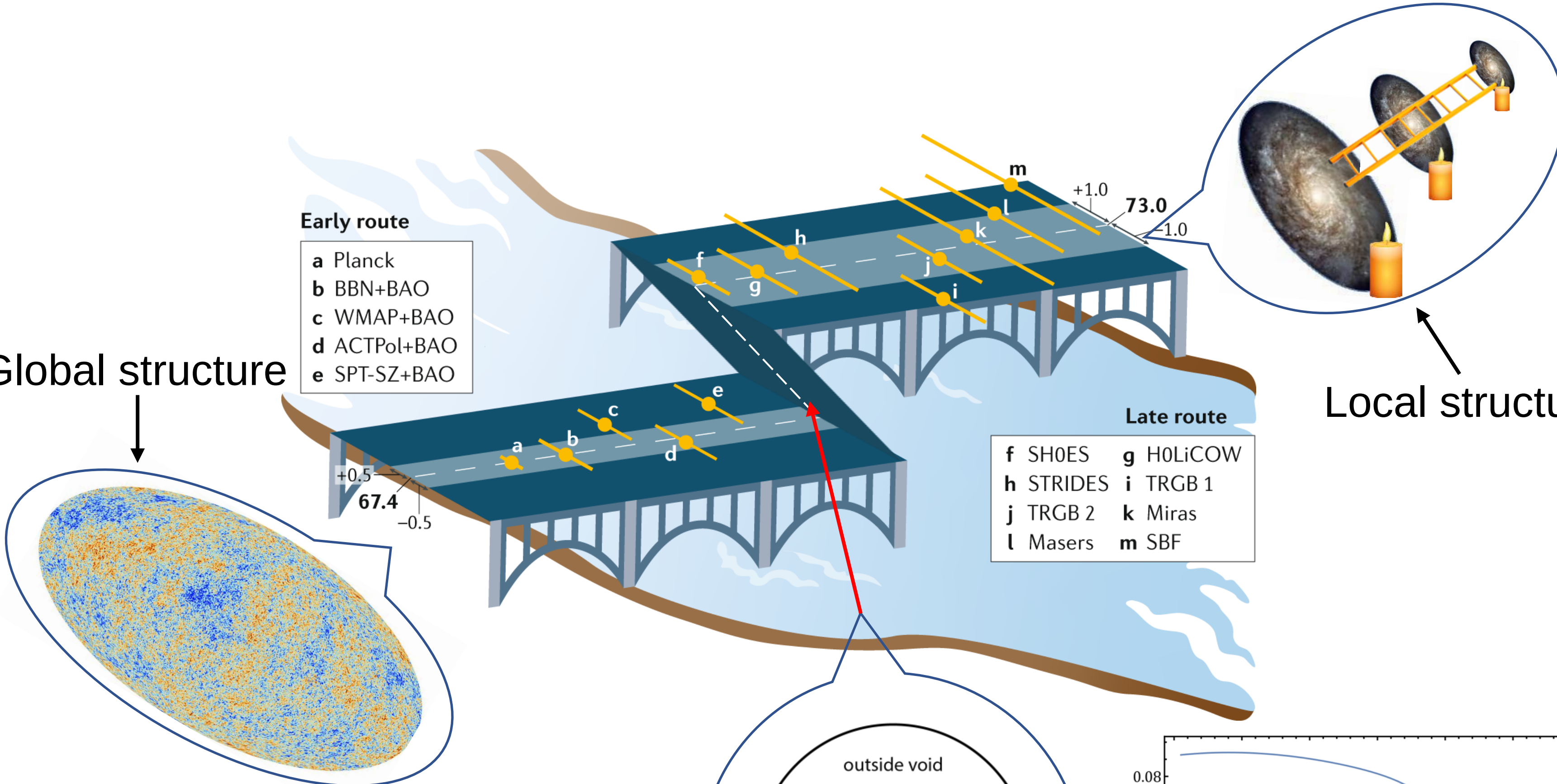
Hubble Tension



Riess, Adam G. "The expansion of the universe is faster than expected." *Nature Reviews Physics* 2.1 (2020): 10-12.

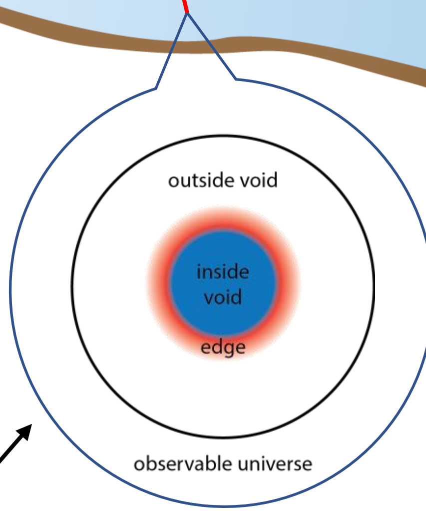
Hubble Tension

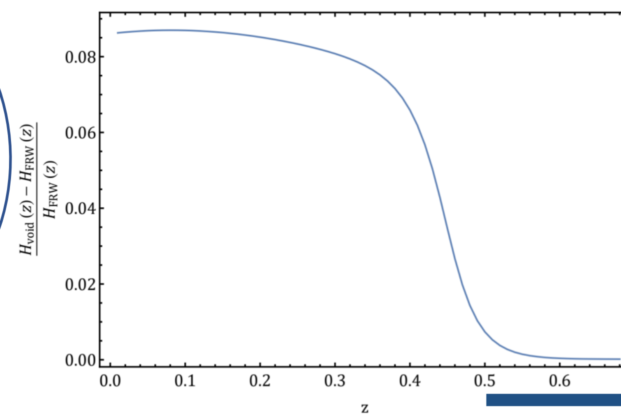
Global structure



Local structure

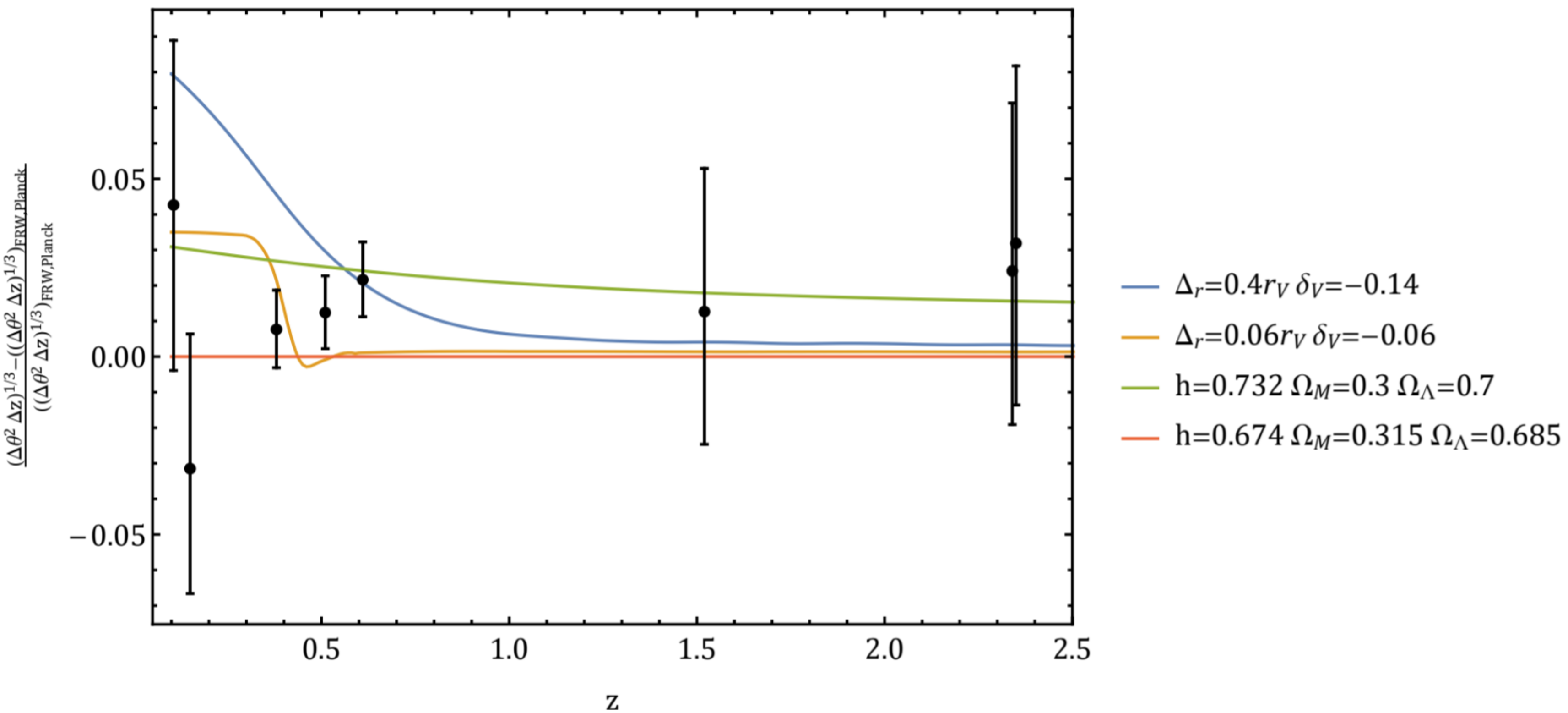
Riess, Adam G. "The expansion of the universe is faster than expected." *Nature Reviews Physics* 2.1 (2020): 10-12.





Local void structure

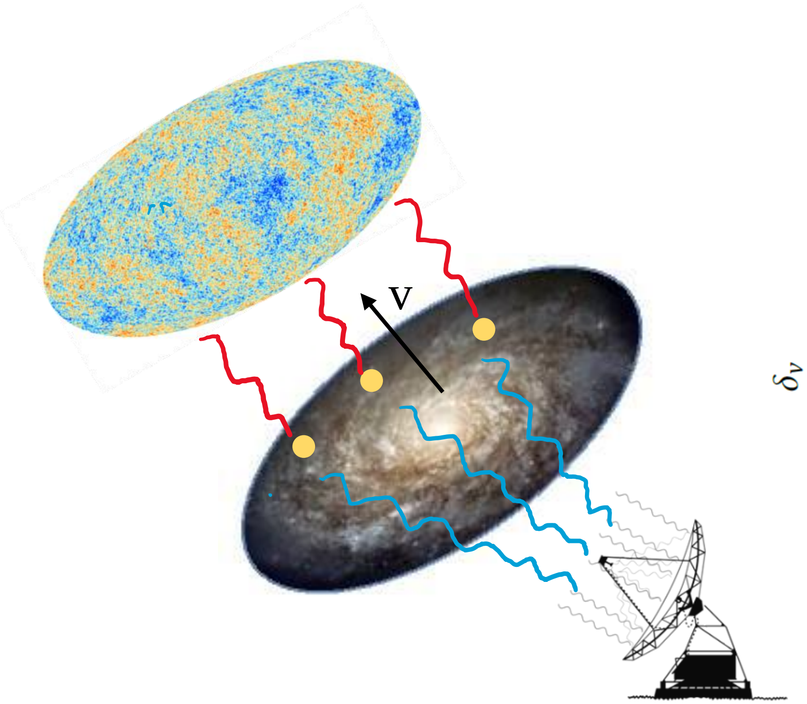
BAO observation



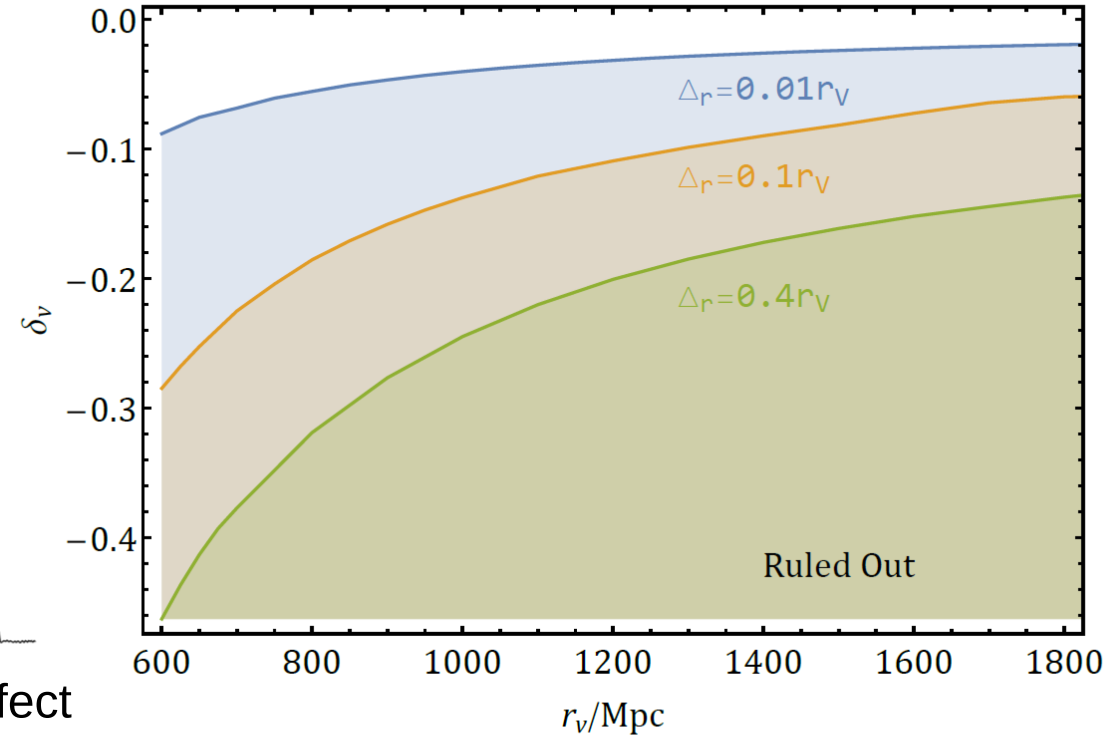
$$(\Delta\theta^2\Delta z)^{1/3} = \frac{z_{BAO}^{1/3} r_d}{D_V^{FRW}(z_{BAO})}$$

$$D_V^{FRW}(z_{BAO}) = \frac{1}{H_0}\left[\frac{z_{BAO}}{h(z_{BAO})}\left(\int_0^{z_{BAO}}\frac{dz}{h(z)}\right)^2\right]^{1/3}$$

Kinematic SZ Effect



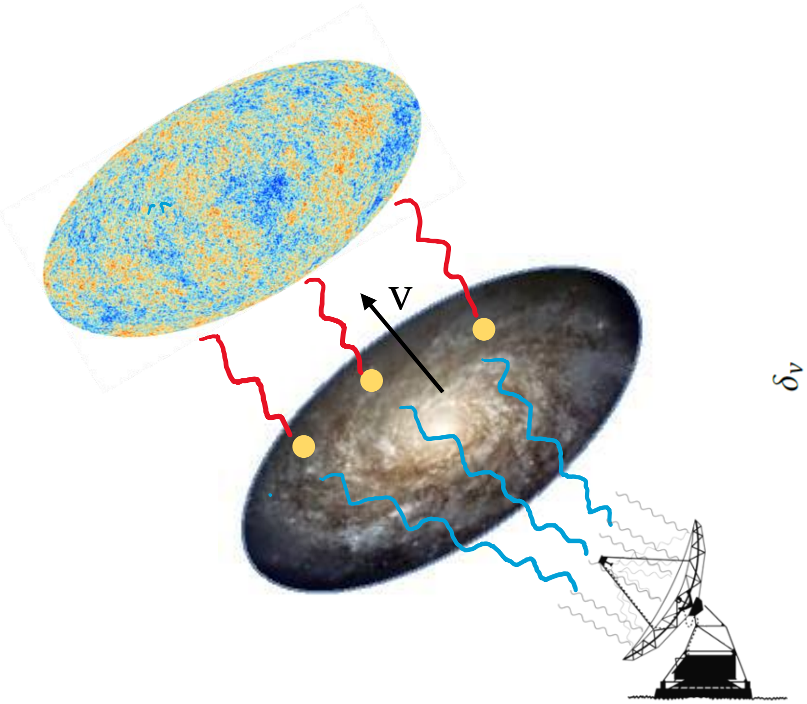
Kinematic Sunyaev-Zeldovich effect



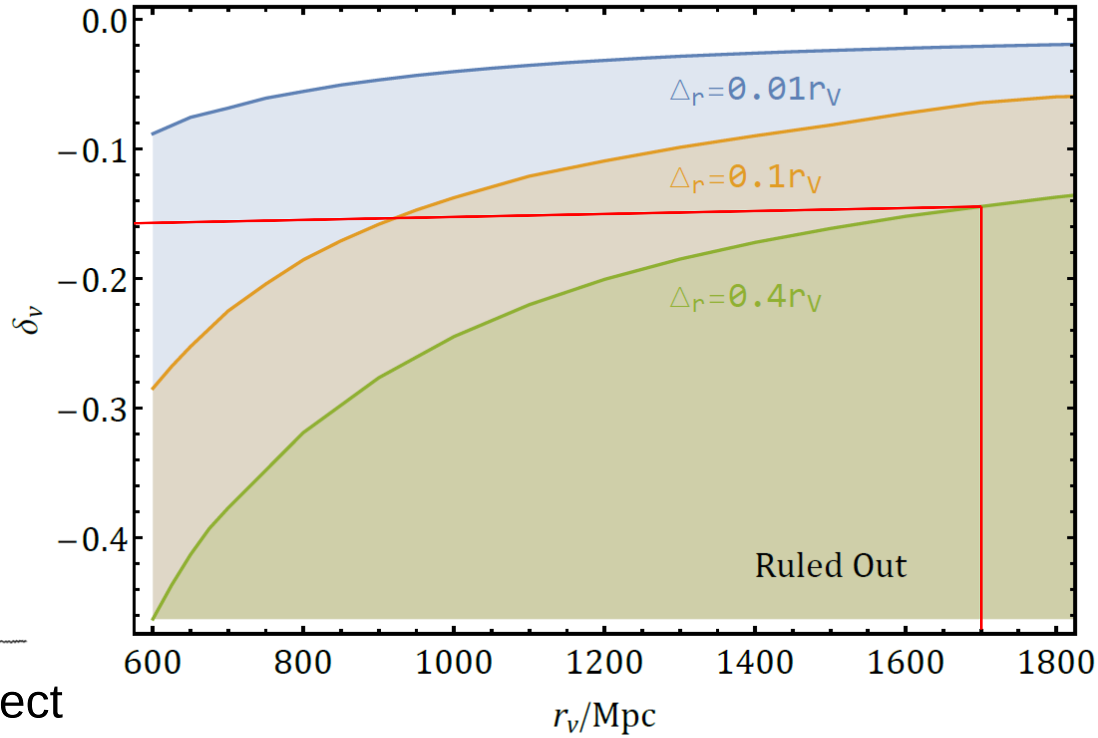
$$\Delta T_{kSZ}(\hat{n}) = T_{CMB} \int_0^{z_e} \delta_e(\hat{n}, z) \frac{V_H(\hat{n}, z) \cdot \hat{n}}{c} \, d\tau_e$$

$$T_{CMB}^2 D_{3000} < 2.9\mu K^2 \quad D_\ell \equiv \frac{\ell(\ell+1)}{2\pi} C_\ell$$

Kinematic SZ Effect



Kinematic Sunyaev-Zeldovich effect



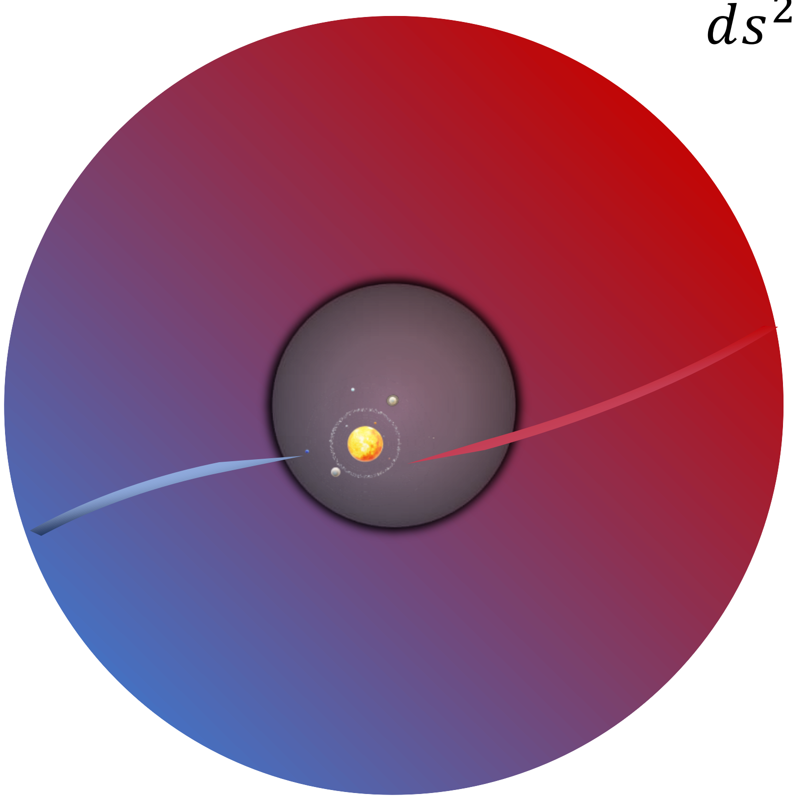
$$\Delta T_{kSZ}(\hat{n}) = T_{CMB} \int_0^{z_e} \delta_e(\hat{n}, z) \frac{V_H(\hat{n}, z) \cdot \hat{n}}{c} \, d\tau_e$$

$$T_{CMB}^2 D_{3000} < 2.9 \mu K^2 \quad D_\ell \equiv \frac{\ell(\ell+1)}{2\pi} C_\ell$$

Cosmic dipoles in a Gpc-scale local void

Tingqi Cai, Qianhang Ding,
Yi Wang, 2211.06857

Geodesic Equations



LTB Metric

$$ds^2 = c^2 dt^2 - \frac{R'(r,t)^2}{1-k(r)} dr^2 - R^2(r,t) d\Omega^2$$

Geodesic Equations

$$\frac{d^2 x^\mu}{d\lambda^2} + \Gamma^\mu_{\alpha\nu} \frac{dx^\alpha}{d\lambda} \frac{dx^\nu}{d\lambda} = 0$$

$$1 + z(\lambda_e) = \frac{\tau(\lambda_r)}{\tau(\lambda_e)}$$

Initial Conditions

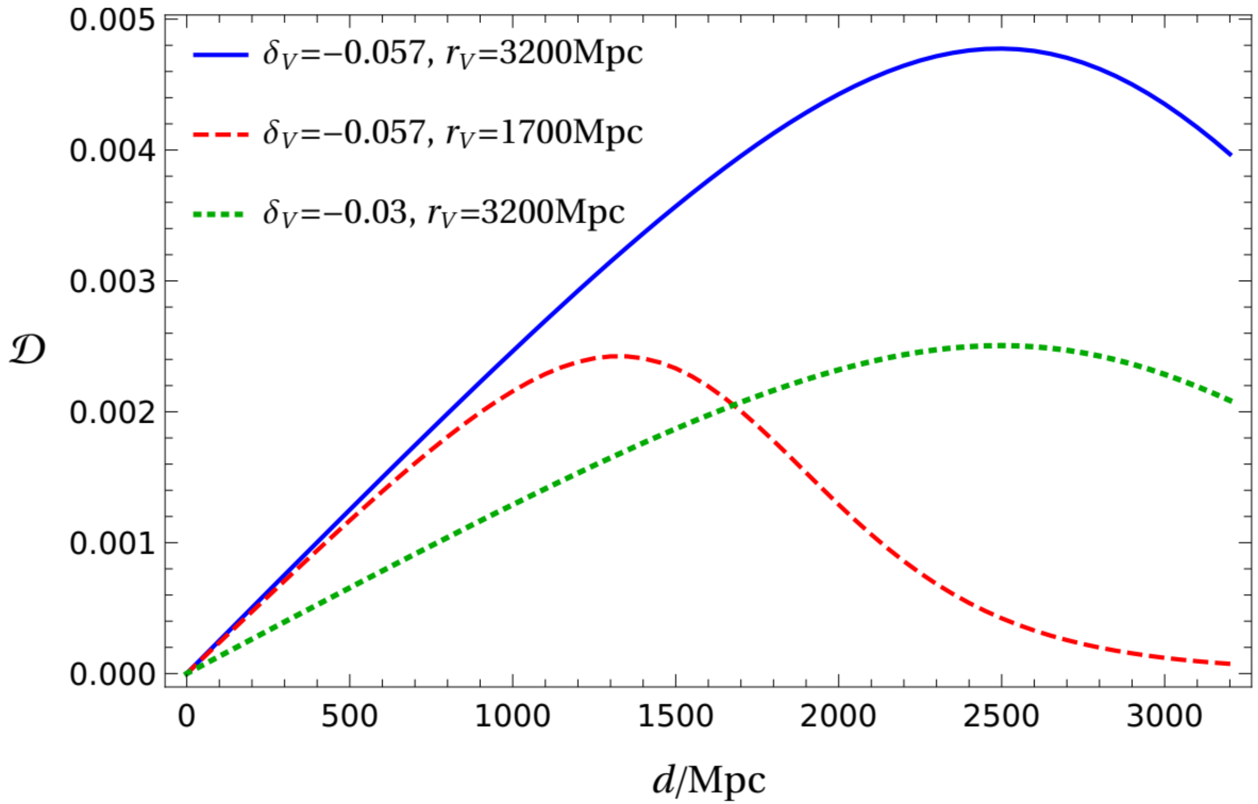
The location of observers r
and the observational angle θ

CMB Dipole

Temperature anisotropy

$$T(\hat{n}) = \frac{T^*}{1+z(\hat{n})} \qquad \frac{\Delta T}{\bar{T}} = \frac{T(\hat{n}) - \bar{T}}{\bar{T}} = \frac{\bar{z} - z(\hat{n})}{1+z(\hat{n})}$$

$$\bar{T} = \frac{1}{4\pi}\int T(\hat{n})\, d\Omega \qquad 1+\bar{z} = \frac{T^*}{\bar{T}} \qquad \mathcal{D} = \frac{2}{\pi}\int_0^\pi \frac{\Delta T}{\bar{T}}(\theta)\cos\theta\, d\theta$$

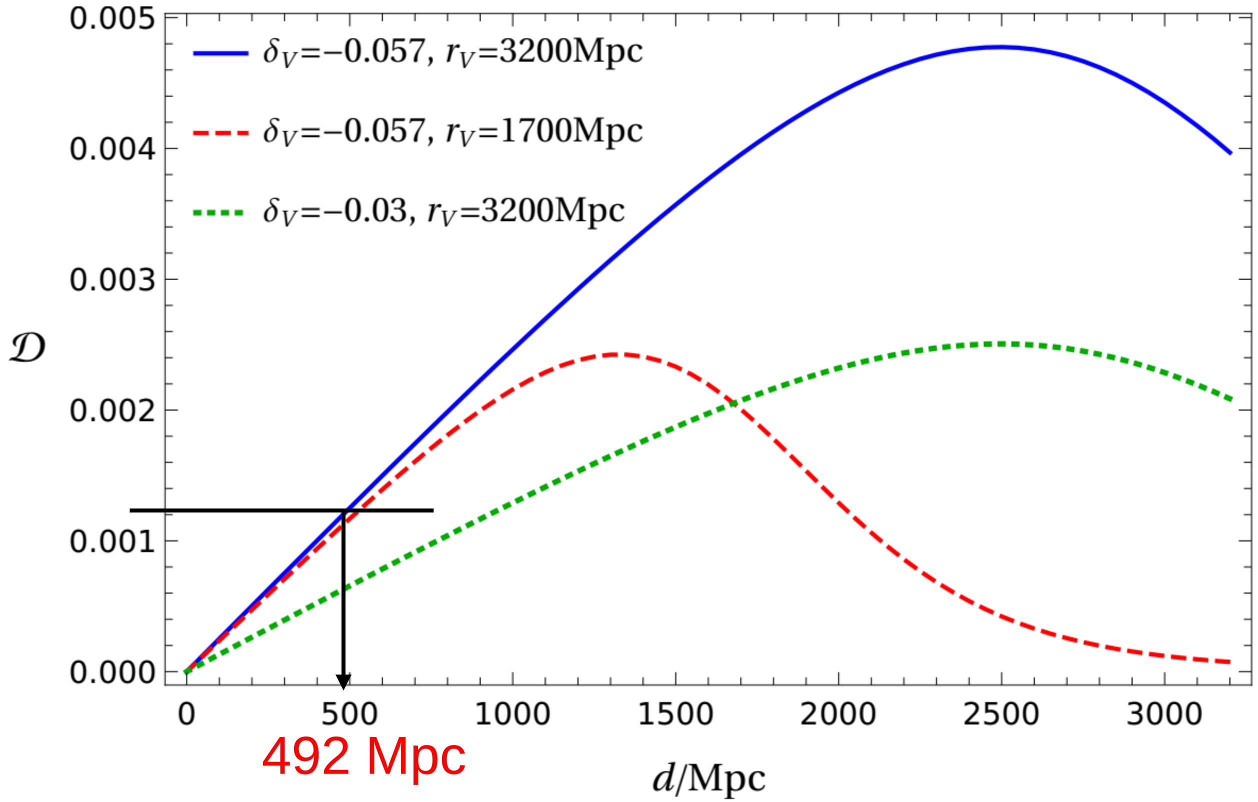


CMB Dipole

Temperature anisotropy

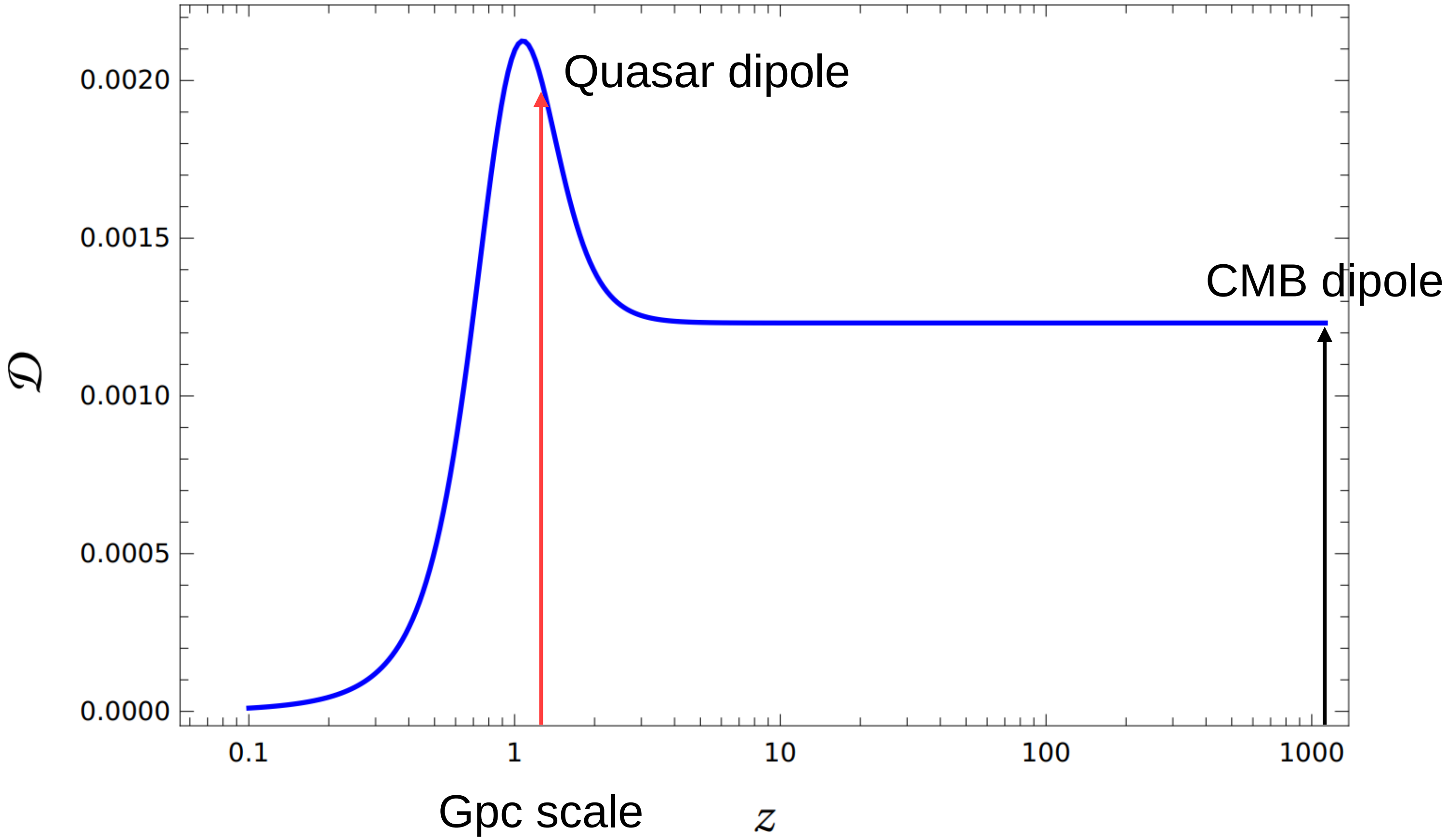
$$T(\hat{n}) = \frac{T^*}{1+z(\hat{n})} \qquad \frac{\Delta T}{\bar{T}} = \frac{T(\hat{n}) - \bar{T}}{\bar{T}} = \frac{\bar{z} - z(\hat{n})}{1+z(\hat{n})}$$

$$\bar{T} = \frac{1}{4\pi}\int T(\hat{n})\, d\Omega \qquad 1+\bar{z} = \frac{T^*}{\bar{T}} \qquad \mathcal{D} = \frac{2}{\pi}\int_0^\pi \frac{\Delta T}{\bar{T}}(\theta)\cos\theta\, d\theta$$



Redshift Dipole

$$\frac{\Delta T}{\bar{T}} = \frac{T(\hat{n}) - \bar{T}}{\bar{T}} = \frac{\bar{z} - z(\hat{n})}{1 + z(\hat{n})}$$



Quasar Dipole

Cosmic redshift in quasar number counting

$$\nu_o = \nu_r \delta \qquad \delta = \frac{1+\bar{z}}{1+z(\hat{n})} \qquad S \propto \nu^{-\alpha} \qquad \frac{dN}{d\Omega} \propto S^{-x}$$

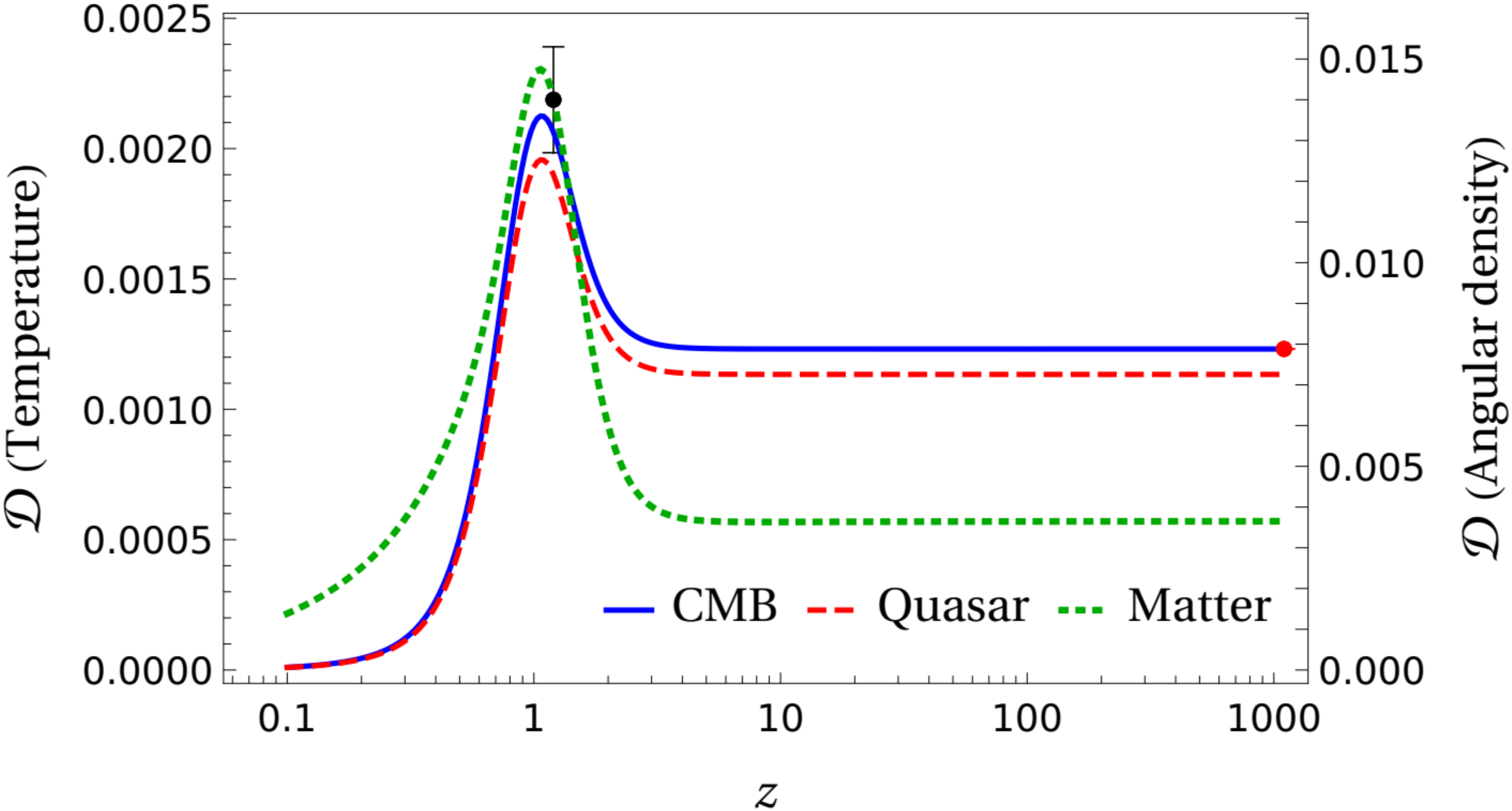
$$\mathcal{D} \cong [2 + x(1+\alpha)] \frac{\bar{z} - z(\hat{n})}{1+z(\hat{n})}$$

Assumption: quasar number density ∝ matter density

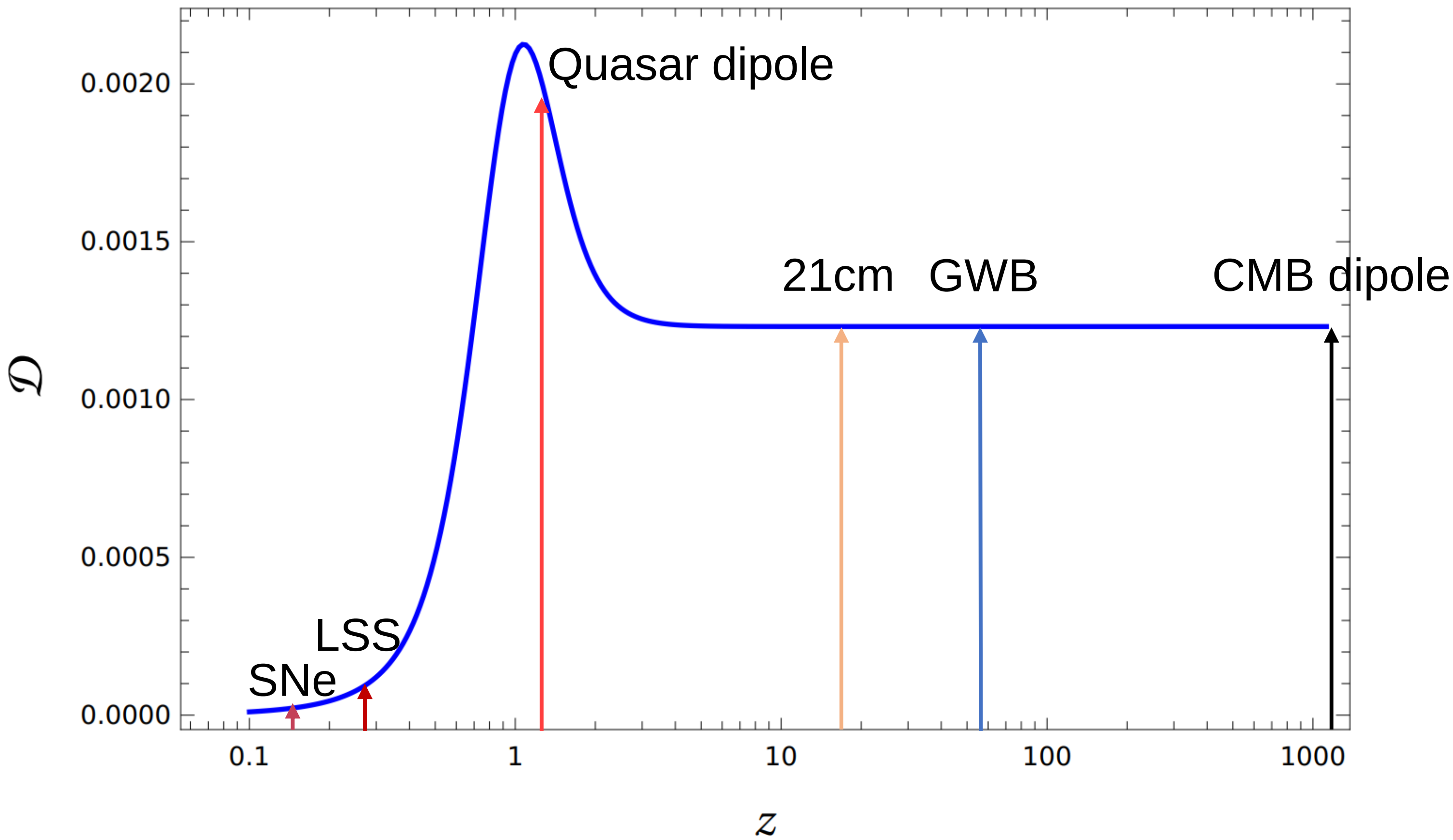
$$\mathcal{D}_Q \sim \mathcal{D}_M$$

$$\frac{\rho dV}{d\Omega}(\hat{n}) \cong \frac{\rho a^3 r^2 dr d\Omega}{d\Omega} = \frac{\rho(\hat{n}) r(\hat{n})^2 dr}{(1+z(\hat{n}))^3}$$

Quasar Dipole



Cosmic Dipole



Cosmic dipoles in global signals indicate the profile of the local structure.


Thank you!